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Importance of Humous Content for Soil Fertility and the Nitrogen Cycle

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Based on results of extended experiments, it is shown that soil fertility is determined mainly by granulometric composition and the content of organic matter. The value of the latter is greater, the less favorable the soil and climate conditions. The close linear dependence between organic matter and the physical properties of soils is confirmed. The quality of humus depends on the ratio of its inert and transformed forms. Standards are presented for classifying soils of central Germany developed on deluvial and loess deposits according to the degree of their supply with organic matter. A dynamic model is developed for computer simulation of the transformation of organic matter in the soil.

The humous content in soil is a decisive indicator of its fertility. It closely correlates with all physical properties of the soil and significantly determines the biological and numerous chemical processes. Organic matter is responsible for the pedogenic process, as Dokuchayev described it [1]. "Soil" arises only with the development of vegetation and the formation of organic matter from parent rock. The properties that determine its fertility, with some exceptions, can be influenced only through the content of organic matter in it.

The definition (concept) of humus is not always unambiguous. Often the concepts of *humus* and *organic matter of soil* (OMS) are applied as synonyms [9], and sometimes they designate different objects, as, for example, it is done in Müller's definition [9]: "Organic matter of soil is defined as the living and dead organic matter integrated in the soil; the former consists of the autochthonous microorganisms inhabiting the soil, or the edafon, and the later consists of humus." The definition of the OMS is incomplete not least of all due to the great spatial and temporal variation of this factor.

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Table 1

Content of Carbon and Fine Particles in Soils of Control Variants of Some Extended Experiments

Experiment site	Content of fine particles (≥ 6.3 μm)	C
	%	
Türo	5	0.35
Gross Kreutz	8	0.46
Münchberg	8	0.55
Seehausen	15	0.65
Galls	13	0.71
Lauchstadt	28	1.60

Based on the results of the investigations of I.V. Tyurin [2], one usually begins from the carbon content in the OMS, equal to 58 percent, and the humous content is calculated by multiplying the content of C_t by the coefficient 1.724. To determine the carbon content, the Tyurin method [2] has become widespread, but often dry combustion is also applied.

Humus Content as a Function of Soil and Climate Conditions and Agricultural Use

Soils differ very strongly with respect to the quality and quantity of humus. The decisive habitat conditions are the parent rock and the granulometric composition, which is defined by it to a significant degree, and also the conditions of wetness and temperature. Concerning quality, the content of "inert" carbon, which practically does not participate in the processes of transformation of carbon (C_i) and its transformable part (C_u) should be distinguished first of all, which is analogous to the widespread concepts relative to the stable "extended" and relatively active "nutrient" humus. The content of C_i correlates very closely with the content of the clay and silt fractions [3, 4, 7]. It can be defined as the carbon content, which does not decrease under conditions of bare fallow, which has not received any fertilizer for a long time.

To express the dependence between the content of fine fractions (clay + silt with particle size ≤ 6.3 μm) as an independent variable (x) and the content of inert C_i as a dependent variable (y), we [7] calculated the regression coefficient, equal to 0.04–0.05. Analogous results came from calculations in which the nitrogen content was taken as a dependent variable. The data in the table show examples of the dependence of the content of C_t on the content of fine fractions in the zero variants (controls, without fertilizers) of some extended experiments. In all cases, the content of C_t slightly exceeds C_i, since additional organic matter enters the zero plot due to small amounts of post-harvest root remains.

The content of carbon present in the soil and capable of being transformed (C_u) depends first of all on the conduct of agriculture and is determined by the quantity and quality of the post-

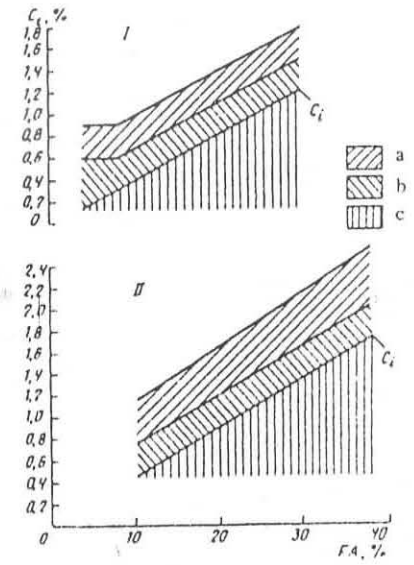


Fig. 1. Standards of classification of automorphic D- (I) and Lö- (II) soils according to their supply with organic matter and according to classes of damage (a) standardized interval, (b) impoverishment with respect to humus, damage class 1, (c) damage class 2 in erosion-prone districts depending on content of fine (≤ 6.3 μm) particles (FA, %). For I: (a) $\hat{y}$ = FA % · 0.04 + 0.6, (b) $\hat{y}$ = FA % · 0.04 + 0.3, (c) $\hat{y}$ = FA % · 0.04. For II: (a) $\hat{y}$ = FA % · 0.05 + 0.65, (b) $\hat{y}$ = FA % · 0.045 + 0.3, (c) $\hat{y}$ = FA % · 0.045.

harvest root remains remaining in the soil and on its surface, organic fertilizers, and also on the intensity of soil cultivation. Greatest enrichment comes from grasses and mixtures of clover and grasses due to the large quantity of roots and to the absence of mechanical cultivation of the soils. In soils formed on deluvial and loess deposits of central Germany, with deep bedding of groundwater, the content of C_u in the plow layer increased from 0.6 to 0.9 percent due to cultivation of grasses and clover-grass mixtures for an extended time. According to data of estimates of 22 national (domestic) and international extended experiments with a total number of 43 comparisons for the main agricultural crops, the following series has been compiled according to their influence on the content of C_u (centner of dry mass of manure/ha):

Grasses, mixture of grasses and clover	40–50
Clover, alfalfa	20–30
Winter wheat, winter barley	16–20

Fodder beans	14–20
Winter rye, summer wheat, oats	15–16
Summer barley	12–14
Maize	10–14
Potatoes	6–8
Sugar beets	4–6
Bare fallow	None

Manure in an extended, systematic application (based on 5 metric tons per ha annually) provides an additional increase in the content of C_u in the plow layer by an average of 0.15 percent. The additive nature of the effects can be proven.

Based on these dependences, standards were developed for classifying automorphic D- and Lö-soils formed respectively on deluvium and loesses according to the degree of their supply with organic matter (Fig. 1).

In this case, the content of inert C for soils on deluvium is calculated by multiplying the amount of fine particles by the coefficient 0.04, and for soils on loess, by 0.045. Under field conditions, the obtained value does not decrease if only there is no plowing of the underlying horizon and/or the surface layer is not disturbed by erosion. In these cases, the soil may be related to the second class of damage, and then it is necessary to apply meliorative amounts of organic fertilizers.

For an adequate supply, there must be a content of transformable carbon (C_u) equal to a minimum of 0.3 percent. If this boundary (C_i + 0.3) is lower (first class of damage), to reach the standard, an increased amount of organic matter must be added.

An excessively high humous content may be economically unfavorable. It is inevitably related to the active liberation of nitrogen, especially in periods when it cannot be used by plants. This nitrogen is lost and may lead to pollution of the environment. For this reason, the standards of organic matter supply also have an upper boundary. If exceeded, the amounts of organic fertilizers should be decreased.

The following conclusions derive from these dependences:

(1) Evaluation of the degree of supply of organic matter to the soil is impossible without knowing its texture (granulometric composition). For example, loess Chernozem at Bad Lauchstadt with a 1.5 percent content of C_t is completely impoverished with respect to organic matter, whereas sandy soil with an 0.9 percent content of C_t is best supplied.

(2) The rates of mineralization calculated on the basis of humus as a whole or on the content of C_t are not informative. It makes sense to relate them only to the transformable part (C_u). For the conditions of central Germany, in accordance with the data presented in Fig. 1, for good supply, the content of C_u in the plow layer must be ~0.5 percent. This amounts to ~200 centner C/ha, and with a C/N ratio of 10, it corresponds to 2000 kg N per ha.

With a mean rate of mineralization of 4 percent C_u, as determined in field experiments, this means the annual liberation of nitrogen from the soil pool in the amount of 80 kg/ha. Since on one

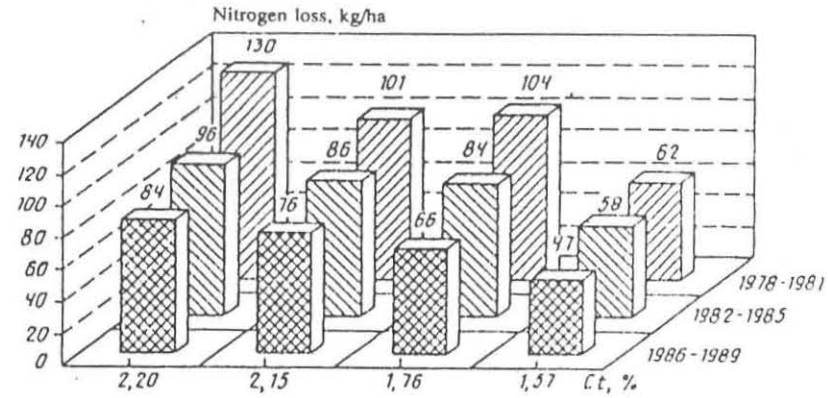


Fig. 2. Stationary experiment with Lauchstadt fertilizers.
Loss of nitrogen as a function of content of C_t.

hand the degree of supply of the soil with organic matter may be very different, and on the other the weather conditions of the year are subject to great fluctuations, the annual liberation of nitrogen fluctuates within broad limits, approximately between 50 and 250 kg N/ha.

An example of the different loss of nitrogen depending on the content of C_t is shown in Fig. 2. After expansion of the range of tasks of investigations in a stationary extended experiment with fertilizers at Lauchstadt in 1978 on the presented variants (fertilizers before 1977: 100 centner manure/ha annually + NPK = 2.20% C_t; 100 centner manure/ha annually = 2.15 C_t; NPG = 1.76 percent C_t; without fertilizers = 1.57% C_t) the loss of N without application of fertilizers through three rotations of the successive crop rotation was investigated: sugar beets, summer barley, potatoes, winter wheat. In the first rotation, the difference was up to 68 kg N/ha; by the third rotation, it decreased to 37 kg N/ha. The small differences in the loss of nitrogen among variants fertilized by manure and NPK beforehand, despite the great differences in the content of C_t, turned out to be unexpected. The cause of this is the great stability of humus in the variant with the use of manure. Here, the nitrogen is liberated more slowly, but its action is more extended than it appears in the third rotation. In estimating the total amounts of nitrogen, it is also necessary to consider its annual supply from "stable sources" (from the atmosphere, etc.), equal to approximately 50 kg/ha.

Decisive for soil fertility and growth processes are not only the content of organic matter in the soil, but also the activity of its transformation. Under natural conditions, the latter is determined by the amount of organic matter capable of transformation and by the habitat conditions. The reserve of transformed organic matter corresponds to the amounts of nutrients accessible to microorganisms and may be determined approximately according to the amount of carbon soluble in hot water (C_{hwl}) [8].

The habitat conditions (temperature, wetness, soil structure) are characterized through the value of WMZ (effective mineralization time) [5], which represents the transformation of normal time on a biological time base. WMZ is an expression of the mean conditions of life of microorganisms in a certain habitat. This value corresponds to the incubation time and optimal conditions and allows an estimate to be made of the biological activity depending on the amount of transformable organic matter.

The biological activity, therefore, is a derivative of WMZ and the active part of C_u and corresponds to the annual amount of C of organic matter of the soil (kg/ha per year) transformable capable of being transformed) under specific conditions of a definite habitat.

WMZ is calculated based on the mean long-term diurnal temperatures, humidity of the air, and precipitation with the use of soil physical parameters typical for the habitat for typical crop rotations.

For Loess Chernozem at Bad Lauchstadt (mean annual amount of precipitation, 480 mm; mean annual temperature, 8.6 °C), the calculated value of WMZ on the average for 10 years was 30 days with fluctuations in individual years from 24 to 40 days; for sandy soil at Türo with 250 mm precipitation and a mean temperature of 8.6 °C, the mean value of WMZ was 40 days. For mountain habitats with an annual amount of precipitation close to 1000 mm and a mean annual temperature of about 6.5 °C, WMZ is only 10 days.

Accordingly, it is necessary to evaluate objectively the different habitats with respect to the necessary expenditures for the reproduction of the organic matter of the soil and liberation of nitrogen from the soil pool.

Influence of Organic Matter on Physical Properties of Soil

Close relationships between the content of organic matter in the soil and the most important physical properties of the soil which determine the yield were investigated repeatedly and proven. However, an unequivocal quantitative evaluation is difficult, since the spatial variability of all measured factors is very large and the difference in the content of C_t in the same habitat with the same granulometric composition of the soil exceeds 1 percent only in exceptional cases.

On Loess Chernozem at Bad Lauchstadt, the former reservoir of manure and *gülle* (German term for liquid manure) was eliminated, and after three years of maize cultivation, this plot was used for investigations of this kind. The content of C_t varied in it from 1.5 to 7.5 percent.

The obtained linear regressions are presented selectively in Figs. 3 and 4.

Without exception, all the investigated soil physical properties depend reliably on the content of C_t with a random error $\alpha = 0.1$ percent. The same dependence was established with respect to the content of N_t.

According to these results, it can be considered that, for a 1 percent increase in C_t, the hygroscopic moisture content increases by roughly 0.7 percent of the soil mass, moisture capacity by

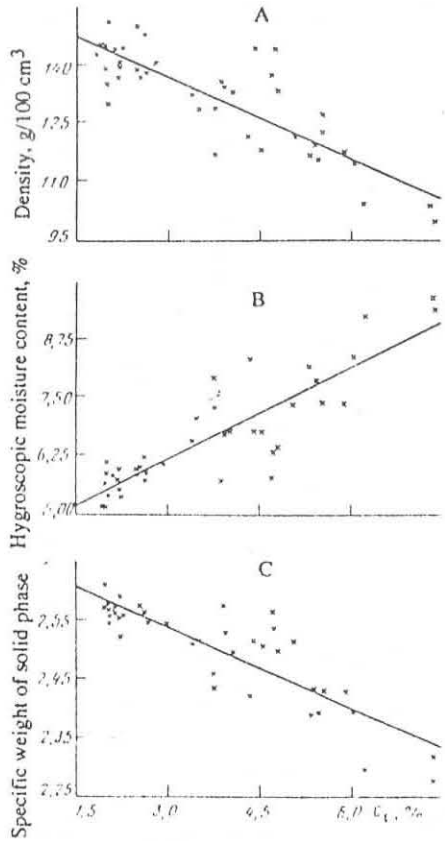


Fig. 3. Linear regression between indices of density (*A*, $r = -0.84$), hygroscopic moisture content (*B*, $r = 0.88$), specific weight (*C*, $r = -0.87$), and content of C_t of soil for layer of 0–30 cm (repetition $n = 40$).

4.0 percent, pore volume by 2.0 percent, and at the same time, the specific weight of the solid phase and the density decrease by 0.05 and 0.07 g/cm^3, respectively.

Also important are the close mutual correlations of the physical factors. The correlation coefficients are 0.81 and 0.98.

According to current theories, it is necessary to begin from the fact that both C_i and C_u identically influence the physical properties of the soil and also the absorption capacity. Following

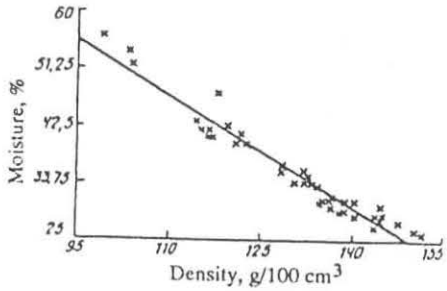


Fig. 4. Linear regression between indices of moisture capacity and density of soil (layer of 0–30 cm, repetition $n = 40$, $r = -0.98$).

from this is the different value of the soil-improving action of organic matter for different soil types. For example, it is very substantial if the absorption capacity of sandy soil increases from 5 to 7 meq due to the application of organic matter, whereas for Chernozem the increase in the absorption capacity from 24 to 26 meq is much less significant.

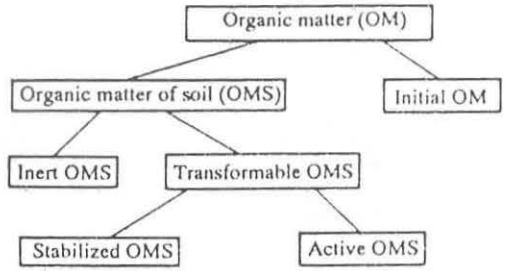
Modeling Transformation and Reproduction of Organic Matter of Soil

In past decades, the number of works modeling transformation and reproduction of organic matter of the soil, based on the achieved level of knowledge and more comprehensive study of the subject, have increased strongly. Based on the approach which existed in the middle of this century, in which, with the aid of simple derivative of the coefficients of humification (isohumus coefficients) and coefficients of mineralization, the static discussion of organic matter has remained at the forefront just the same, in subsequent years, complex dynamic models have become the center of attention. Simultaneously, the center of gravity of these works has shifted from the production of organic matter of the soil to the study of soil nitrogen.

Interest in such works has been maintained on one hand by the strengthened application of mineral nitrogen fertilizers, which as a whole gave the nitrogen problem increased importance, and on the other hand by the development of computer technology, with whose aid more complex problems can be solved rapidly and a large amount of data can be processed in a short time.

Intensive works have been carried out in parallel on the application of fractionation of organic matter and on the methods of determining the degree of transformation (transformability) of its C and N fractions, as well as on explaining their cycle in processes of mineralization and immobilization.

The starting point of investigations on modeling the transformation of C and N at Bad Lauchstadt consisted of works on the balance of organic matter of the soil carried out in the middle of the 1970s.



Reproduction of the organic matter of the soil with the aid of the addition of organic fertilizers and post-harvest root remains was calculated using coefficients of reproduction of the humus through the equivalent of dry material of manure. Primarily extended field experiments have served as an experimental foundation for selecting the parameters.

A dynamic model has been developed based on this statistical method. It includes examination of the dynamics of C and N and the variation of the C/N ratio and serves for computer simulation of the transformation of organic matter in the soil, including all important processes of the dynamics of nitrogen. All calculations are carried out with 1-day spacing for 20 layers 20 cm each and includes the following processes:

- Loss of nitrogen by plants and supply of nitrogen with mineral fertilizers from the atmosphere and due to the fixation by leguminous crops
- Migration of nitrogen in soil profile
- Gaseous losses of nitrogen
- Mineralization and reproduction of organic matter of soil
- Nitrification
- Supply and transformation of organic fertilizer and also post-harvest root remains

Along with data on the location of the soils, annual weather conditions, and agrotechnical measures, as starting values, we must know the distribution of mineral nitrogen (N_{an}) in the profile and the content of transformable organic matter.

A prerequisite for such a model to function was the fairly accurate determination of the required parameters, especially the following: mass and quality of post-harvest root remains; depth of root penetration; supply of nitrogen from the atmosphere and "other sources"; assimilation of nitrogen by plants; fixation of nitrogen by leguminous crops; losses of nitrogen.

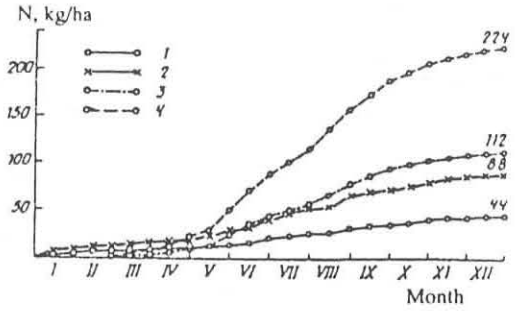


Fig. 5. Mineral nitrogen from organic matter of soil as a function of level of its content ((1, 3) low, 1984 and 1982, respectively; (2, 4) high, 1984 and 1982) and weather conditions during the course of a year. Example of modeling for Loess Chernozem.

Modeling the process of transformation of organic matter also requires separation of all the organic matter found in the soil into individual fractions, which are characterized according to their role in the transformation process (flowchart).

The total content of carbon in the soil (C_t) is divided, as shown in the flowchart, into "inert' and "transformable" portions. For mineralization and together with it the liberation of nitrogen, only the transformable carbon has value. Changes in the state of the supply to the soil in terms of the value of C_t appear only after an extended time (> 10 years). They first become measurable in the most easily transformable fractions. Carbon soluble in hot water (C_{hwl}) includes only simple organic compounds, as well as easily depolymerizable carbohydrates and microbial biomass. It is the most easily transformable part of the C_u fraction. Close relationships between C_{hwl} and the liberation of CO_2, as well as the mineralization of nitrogen-bearing components, were established in numerous investigations and confirmed in extended experiments.

In the simulation model, the transformable carbon is divided into "stable" and "active" fractions, and in this case, all fractions of transformable C and components of the initial organic matter are found in a state of dynamic equilibrium.

The application of the model makes possible, in particular, the following:

- The conclusion about the distribution of the content of N_{an} in the soil and also about the supply of nitrogen from the organic matter of the soil and the initial organic matter
- Evaluation of the influence of post-harvest root remains and organic fertilizers on the nitrogen regime and the reproduction of the organic matter of the soil as a basis for planning crop rotations, planning the application of fertilizers and degree of balance of the organic matter of the soil
- Investigations of the effectiveness of applying fertilizers and consideration of the possible pollution of the environment

- Calculation of the indices (values) of biological activity of the soil, which depends, on one hand, on the amount of substrate accessible to microorganisms, determined by the transformable carbon and on the other on the effective time of mineralization as an indicator of the conditions of their life.

Figure 5 presents an example of the simulation of the dependence of the activity of nitrogen mineralization on the supply of organic matter to the soil and weather conditions during the course of the year.

Conclusion

(1) Soil fertility is determined mainly by its granulometric composition and by the content of organic matter (OMS). It is possible to influence soil fertilizer directly by means of applying organic matter.

(2) The value of the OMS is greater, the less favorable the soil climate conditions (sandy soils with a low absorption capacity, structureless loamy and clayey soils, districts of insufficient moisture supply). In this case, one should distinguish the action of organic matter of soil as a source of nutrients and as a soil-improving means. Depending on the soil and climate conditions, both these functions may assume dissimilar values.

(3) The indices C_t and N_t are applied as criteria of the humous content. The C/N ratio may serve as a monitor of the quality of organic matter.

(4) A close linear dependence exists between the content of organic matter of the soil and the physical properties of the soil which determine the yield.

(5) The content of inert organic matter in the soil (C_i) is determined primarily by the granulometric composition and practically does not submit to regulation. All changes affect to a greater of lesser degree by the transformable part of the organic matter (C_u) and the nitrogen annually liberated from it.

(6) From the results of extended experiments, it can be concluded that, with an unchanged system of farming, a constant "level of humous content" (dynamic equilibrium) is established. For this, a period of at least 20 years is necessary, depending on the original level. In a state of this equilibrium, the amount of organic matter annually arriving corresponds to the amount of mineralizable organic matter. Soil "normally" supplied by organic matter contains 200 centners of transformable carbon per hectare of 2000 kg of transformable nitrogen per ha; with a mean rate of mineralization of 4 percent, about 80 kg N/ha is mineralized annually.

Upon a change in the farming system, the direction of the change in the content of organic matter of the soil depends on the original level. With a low original level, the same measures may cause an increase, and with a high original level, it may cause a decrease in the content of organic matter of the soil.

(7) Nitrogen of mineral fertilizers and nitrogen in the soil, especially under favorable habitat conditions, are mutually interchangeable.

(8) The influence of agricultural crops on the organic matter of the soil depends on the amount and material composition of the post-harvest root remains left after gathering the harvest or in the soil, the duration of the growth period, and the intensity of the soil cultivation.

Under conditions of central Germany, ~60 percent of the demand for organic matter is covered due to the post-harvest root remains.

(9) All agricultural and horticultural measures should be directed toward maintaining a content of transformable carbon (C_u) in the plow layer within the standardized interval of 0.3 and 0.7 percent. An excessively high content of humus is inevitably related to high indices of liberation and loss of nitrogen.

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